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Big Bang Nucleosynthesis: Accelerator Tests and Can Ω_B Really be Large*

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ABSTRACT

The first collider tests of cosmological theory are now underway. The number of neutrino families in nature, N_ν, plays a key role in elementary particle physics as well as in the synthesis of the light elements during the early evolution of the Universe. Standard Big Bang Nucleosynthesis argues for $N_\nu = 3 \pm 1$. Current limits on N_ν from the CERN $\bar{p}p$ collider and e^+e^- colliders are presented and compared to the cosmological bound. Supernova SN 1987A is also shown to give a limit on N_ν comparable to current accelerator bounds. All numbers are found to be small thus verifying the Big Bang model at an earlier epoch than is possible by traditional astronomical observations. Future measurements at SLC and LEP will further tighten this argument.

Another key prediction of the standard Big Bang Nucleosynthesis is that the baryon density must be small ($\Omega_B \lesssim 0.1$). Recent attempts to try to subvert this argument using homogeneities of various types are shown to run afoul of the ^7Li abundance which has now become a rather firm constraint.

INTRODUCTION

The interaction between cosmology and particle physics has grown at an explosive rate during the last decade. One of the first predictions to come from physics at the frontier of these fields was that Big Bang nucleosynthesis constrains[1] the number of light ($\lesssim 10MeV$) neutrino flavors, N_ν; this constraint probably limits the number of quark and charged

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lepton flavors as well. In fact when the cosmological limit was first proposed the particle physics limits were in the thousands, and tradition had it that new energies would lead to new particle generations. Thus the cosmological statement of small numbers seemed very risque. Such a cosmological constraint is extremely important since particle theory in general does not limit N_ν. It is therefore of great relevance that this cosmological prediction[1] is finally being tested in the laboratory by collider experiments. This first test of cosmological theory at a high energy physics facility will provide a check on the hot Big Bang model back to an earlier epoch than is feasible with any of the traditional astronomical techniques.

Steigman in his presentation here reviewed the current status of the arguments[3,4] from primordial nucleosynthesis which lead to the present bound $N_\nu \leq 4.0$ (the "standard" $N_\nu = 3$ is completely consistent with Big Bang nucleosynthesis). Next, we examine the possibilities for neutrino counting at $\bar{p}p$ and e^+e^- colliders, present the new limits from CERN and PEP and discuss the future prospects. It should be noted that cosmological and accelerator experiments do not "measure" exactly the same quantities but are quite complimentary. It is shown that the standard Big Bang model is in very good shape. At the end we turn our attention to another prediction of the standard model, namely the baryon density. We show that recent attempts to get around the constraint that $\Omega_B \lesssim 0.1$ run afoul of the lithium constraint.

NEUTRINO FAMILIES: THE QUARK-LEPTON CONNECTION

At present, three generations of quarks and leptons are known. Only the t-quark and the τ-neutrino remain to be completely confirmed. As is well known, each generation contains six quarks (3 colors of "up" quarks with $Q = +2/3$ and 3 colors of "down" quarks with $Q = -1/3$) and two leptons (a charged lepton and a neutrino). It is of fundamental importance to determine if additional families of quarks and leptons exist.

In the past, the discovery of a new generation has been made by first discovering a charged lepton. This was due largely to the lower mass of the charged lepton and/or the cleaner experimental signature (e.g.: consider the μ-lepton versus the strange or charmed quark). Today, we may be in a similar situation in that either a charged lepton from W or Z decay or, an additional neutrino flavor could provide the first evidence for another generation. In contrast, the quarks of a fourth generation, if it exists, may well be out of reach of the present colliding beam machines. In contrast, a bound to the total number of neutrino flavors may provide an upper limit to the number of quark-lepton generations.

A remarkable aspect of the hot Big Bang model for the evolution of the Universe is the dependence of primordial nucleosynthesis—in particular, the synthesis of ^4He—on N_ν, the number of light neutrino ($m_\nu \lesssim 10 MeV$) flavors.[1,2,3,4] The present limit on the number

of neutrino families derived from $Z°$ decay is completely consistent with the cosmological bound. This represents the first accelerator test of cosmology. The cosmological bound limits the number of "relativistic degrees of freedom" which were present during Big Bang nucleosynthesis whereas the accelerator data limits the number of particles, which could be very massive ($\lesssim M_Z/2$) but, must couple to the $Z°$. That the two bounds very nearly coincide helps rule out (or, at least, constrain) the numbers of new "heavy" neutrinos and/or "light"exotic particles.

Laboratory experiments show directly that the ν_e and ν_μ are light (in the context of our discussion). Despite an heroic effort to lower the upper limit to the mass of the τ-neutrino, laboratory data[6] still permits a "heavy" ν_τ. However, by combining astrophysical and accelerator data, it has been argued that the ν_τ must be light . For convenience, we shall write $\delta N_\nu = N_\nu - 3$. Although we expect $\delta N_\nu \geq 0$, if the cosmological bound should eventually turn out to yield $\delta N_\nu < 0$, the question of the ν_τ mass might have to be reopened. In fact current best fits to astrophysical data put $N_\nu \sim 2.6$. However, uncertainties clearly allow values of 3; 4 is getting a bit marginal.

NEUTRINO COUNTING AT COLLIDERS: PRESENT RESULTS AND FUTURE PROSPECTS

The counting of neutrino families at colliders relies on the production and decay of real or virtual $Z°$ bosons. Within the framework of the standard electroweak theory the $Z°$ is universally coupled to leptons and quarks. Thus, in the decay of the $Z°$, the branching ratio to the standard 3 neutrino species—as well as to new families—is prescribed. Basically, there are three ways to count neutrino families at colliders[5]:

A. Direct detection of $Z° \rightarrow \nu_i \bar{\nu}_i$,

B. Measurement of the total width of the $Z°$ to determine the neutrino partial width $\Gamma(Z° \rightarrow \nu_i \bar{\nu}_i)$.

C. Deviation of $\frac{M^2_\omega}{M^2 cos^2\theta_\omega}$ from unity caused by radiative corrections which increase with N_ν.

Technique (A) can be used at a $\bar{p}p$ or an e^+e^- collider by detecting either

$$\bar{p}p \rightarrow Z° + gluon \tag{1}$$

$$e^+e^- \rightarrow Z° + photon \tag{2}$$

Recently both processes (1) and (2) have been observed and lead to limits on δN_ν, with process (2) occurring via virtual $Z°$'s at present since e^+e^- energies are below $M_{Z°}$ until SLC and LEP begin operations.

The measurement of the Z° width can be carried out directly or by a determination of the ratio of Z° to W widths. The direct measurement from the CERN collider experiment gives a very poor limit to δN_ν at present. For $\bar{p}p$, technique B gives the best present limit on δN_ν. This uses a directly measured ratio of the $W \to e\nu_e$ and $Z^\circ \to e^+e^-$ rates to give

$$R = \frac{R(W \to e\nu_e)}{R(Z^\circ \to e^+e^-)} = (\Gamma_Z/\Gamma_W)\left(\frac{\Gamma_{W \to e_\nu}}{\Gamma_{Z \to e^+e^-}}\right)\left(\frac{\sigma_{W^+} + \sigma_{W^-}}{\sigma_Z^\circ}\right).$$

The key idea of this technique is that $\Gamma_{W \to e_\nu}/\Gamma_{Z \to e^+e^-}$ is reliably calculated in the standard model once $\sin^2\theta_W$ is known and $(\sigma_{W^+} + \sigma_{W^-})^\sigma Z^\circ$ is determined from QCD calculations.[7] Actually the calculation of the ratio of cross sections is more reliable than the individual terms due to cancellations in the ratio. Finally, it is possible to determine Γ_W if we know all of the important decay modes of the W. The Z° and W widths are given as [including the possiblity of 4th generation charged lepton (L) and the t quark].[5,8]

$$\Gamma_Z = [2.54 + \Gamma_{Z \to t\bar{t}} + \Gamma_{Z - L\bar{L}} + 0.17\delta N_\nu]GeV \tag{11}$$

and

$$\Gamma_W = [2.2 + \Gamma_{W \to t\bar{b}} + \Gamma_{W - L\nu_L}]GeV \tag{12}.$$

The present limit on the mass of a possible 4th generation lepton reduces the contribution to the Z° width to a negligible value. This is not true however for the W width. Thus, the intrinsic uncertainty in the ratio of Z to W widths comes from the t and L mass (or existence) and limits the accuracy of this technique in determining δN_ν. While it may be relatively easy to reach an uncertainty in δN_ν of ~ 2, to achieve greater accuracy will be very difficult with the ratio of widths technique. When adequate statistics are collected for processes (1) and (2) it will be possible to measure δN_ν to $\lesssim \pm 1$.

A variant on direct width measurements is to study the partial width for the process $Z^\circ \to \nu\bar{\nu}$ by

$$\gamma + Z^\circ \to \gamma + \nu\bar{\nu}$$

and look for the scattered γ in coincidence with nothing (the nondetectable neutrinos). This can be done for real Z°'s at SLC or LEP or for virtual Z°'s using heavy $q\bar{q}$ states

$$\gamma + (q\bar{q}) \to \gamma + (virtual Z^\circ) \to \gamma + \nu\bar{\nu}.$$

We now turn to the present measurements of, or limits to, δN_ν. Fig. 1 shows a comparison of the limits reached with the various techniques. The UA1 and UA2 results on the ratio of widths can be combined to give[5]

$$\delta N_\nu \leq 2.$$

A similar bound–using virtual Z°'s–from $e^+e^- \to \gamma\nu\bar\nu$ is obtained from the data of MAC and ASP at PEP and CELLO at PETRA.[9]

That δN_ν is small is also suggested by the data from method C which is consistent with $M_W^2 = M_Z^2(1 - \sin^2\theta_W)$. Radiative corrections due to <u>extra</u>, low mass neutrino flavors with corresponding new quarks would cause a deviation in this relation.[10] Limits from the data suggest $\delta N_\nu \lesssim 2$.

These measurements are all in excellent agreement with the cosmological results (see Fig. 1). From current experimental data we may conclude that, at most, there may be a fourth or possibly a fifth family of quarks and leptons. Given the present uncertainty ($\sim \pm 2$) in the neutrino counting techniques, the direct search for a fourth generation lepton is of great significance.

SUPERNOVA LIMITS

It is now well established that Kamioka and IMB detected[11] antielectron neutrinos from SN 1987A. Due to neutral currents, supernovae generate[12] all types of neutrinos with masses $\lesssim 10 MeV$. Since the total energy radiated in neutrinos is the neutrons for binding energy $\sim 2\times10^{53} ergs$, it is clear that too many additional neutrino species would dilute the number at detectable $\bar\nu_e$'s before the observations.[13] Plugging in numbers and uncertainties, one finds that $\delta N_\nu \lesssim 4$ from this technique.[14] Thus giving a completely independent argument that δN_ν is small as predicted by cosmology.

LI AND Ω_B

With the increasing success of the N_ν prediction, confidence continues to grow on the standard cosmological model. One important astrophysical constraint of the standard model[15] is $\Omega_B \lesssim 0.1$. Recently possible loopholes in this constraint have received publicity. These loopholes come from the possibility that the quark-hadron transition can produce variations in n/p ratios in the early Universe and that mixtures of such variable n/p ratios can fit D, ^3He, and ^4He abundances[16] for $\Omega_B \sim 1$. These models do indeed manage to fit D/H with a high Ω_B and D/H was the original reason used for limiting Ω_B. However any model with large variations seems to inevitably over produce ^7Li. This occurs because Li observations fall exactly at the Li production minimum in the standard model. Thus mixing of larger or smaller density values moves away from the minimum and is incapable of giving such small values. In particular, as Alcock et al.[16] show, models which have enough n/p variations to yield $\Omega_B \sim 1$ produce more ^7Li than is observed in Pop I which in turn is ~ 10 times the probable primordial Pop II abundance.

Although Li abundances were less of a constraint a few years ago, it has now been shown by three independent groups that the Pop II abundances are really at Li/H $\sim 10^{-10}$ which

precisely hits the minimum of the standard model.[17] These new measurements range over Pop II metallicities, and thus cannot be fit by any standard convective depletion of Pop I abundances. In addition Baade[18] has found that Li in the LMC is consistent with the Pop II value. Since the LMC is metal deficient relative to Pop I (yet metal rich compared to Pop II) this shows that the ^7Li of Pop I does indeed seem to be an enhancement over Pop II rather than Pop II being some special depleted case. The enhancement mechanism is presumably

$$^3HE + \, ^4He \rightarrow \, ^7Be \rightarrow \, ^7Li$$
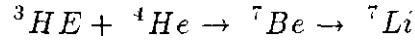
in convective zones. Such Li production is seen in some red giants so we know ^7Li is enhanced in the galaxy. In addition we know that ^6Li is not made in stars nor in the standard Big Bang but must come from cosmic ray spollation over the history of the galaxy. Any large scale Li destruction mechanism would preferentially destroy ^6Li. Thus it would be difficult to lower the excess ^7Li produced in these variable n/p models even down to Pop I abundances and still have the observed ^6Li found in the solar system.

Admittedly the details of Li production and destruction in stellar convective zones is only qualitatively not quantitatively understood. However considering the difficulties of quantitatively understanding turbulence, convection, etc. (weather) everything really fits together quite well. The detailed quantitative weather next week in New Orleans might be hard to predict but the qualitative statement that it will be warmer in New Orleans than at the North Pole is hard to argue against. Similarly the lack of a full quantitative understanding of stellar convection does not really enable one to overthrow all of the well established lithium trends. As Kawano et al.[17] argue, lithium has come of age as a cosmological problem and it's not deuterium that has now become the strongest argument for $\Omega_B \lesssim 0.1$.

ACKNOWLEDGEMENTS

REFERENCES

1. G. Steigman, D. Schramm and J. Gunn, Phys. Lett. B66, 502 (1977).

2. G. Steigman, in this volume (1987).

3. J. Yang, M.S. Turner, G. Steigman, D. Schramm and K. A. Olive, Ap. J. 281, 493 (1984); A.M. Boesgaard and G. Steigman, Ann. Rev. Astron. Astrophysics 23, 319 (1985).

4. G. Steigman, K. A. Olive, D. Schramm, M. S. Turner, Phys. Lett. B76, 33 (1986).

5. D. Cline, D. Schramm and G. Steigman, Comments on Nuclear and Particle Physics (and references therein) (1987).

6. Proc. Recontre de Moriond on Neutrino Masses, ed. Tran Thanh Van. (1986).

7. D. Cline and J. Rohlf, UA1 technical note TN 83-40 (1983), unpublished; N.B. Deshpande et al., Phys. Rev. Lett. 54,1757 (1985); N. Cabibbo, Proc. Third Topical Workshop on $p\bar{p}$ Collider Physics (Rome, January 1983) p. 567 (Geneva 1983); F. Halzen and K. Mursula, Phys. Rev. Lett. 51 (1983).

8. D. Schramm and G. Steigman, Phys. Lett. 141B, 337 (1984).

9. T. Levine, Proc. of the SLAC Summer Institute 1986; U. of Wisc. Preprint No. WISC-EX-86/275 and U. of Wisc. PhD Thesis.

10. G. Altarelli, Ecole d'Ete de Physique des Particules 1986 (as referenced by H. Reeves, 1986 Saclay Preprint).

11. Bionta, R. et al., Phys. Rev. Lett. 58, 1494 (1987); Hirata, K., et al. Phys. Rev. Lett. 58, 1490 (1987).

12. D. Schramm and W.D. Arnett, Ap. J. (1975).

13. D. Schramm, Proc. Recontre de Moriond (1987).

14. D. Schramm, Comments Nuc. Part. Phys. (1987); J. Ellis and K. Olive, Phys. Lett. (1987).

15. J. Gott, J. Gunn, D. Schramm and B. Tinsley, Ap. J. and references therein (1974).

16. C. Alcock, G. Fuller and G. Mathews, Ap. J. (1987); J. Applegate, C. Hogan and R. Scherrer, Phys. Rev. D35, 115 (1987).

17. L. Kawano, D. Schramm and G. Steigman, Fermilab preprint (and references therein) (1987).

18. D. Baade, Proc. ESO workshop on SN 1987A.

FIGURE CAPTIONS

1. Present limits to N_ν from cosmology, $p\bar{p}$ and e^+e^- experiments (from ref. 5).

2. Mass fraction of helium -4, Y_p versus the baryon-to-photon ratio, N, for $N_\nu = 2, 3$ and 4. The three curves at each N_ν correspond to neutron half-lives of 10.4, 10.5 and 10.6 min. The horizontal dotted line is the current 3τ upper limit on ^4He from observations. While it is not impossible that systematic errors could raise this to 0.25 and thus marginally allow $N_\nu = 4$, higher values seem well excluded. However it is far more difficult to exclude systematic errors that could give lower values for He. Thus no lower bounds have been drawn. The vertical dotted lines correspond to upper and lower bounds on the baryon-to-photon ratio coming from ^3He, D and ^7Li. It is IMPORTANT to note that ^7Li independently supports the independent limits previously derived from ^3He and D. The current central observed abundance values of Y_p and N are 0.235 and 4×10^{-10} which yield $N_\nu \sim 2.5$. Obviously $N_\nu = 3$ is a perfectly allowed value and a good fit to the data once error bars are included.
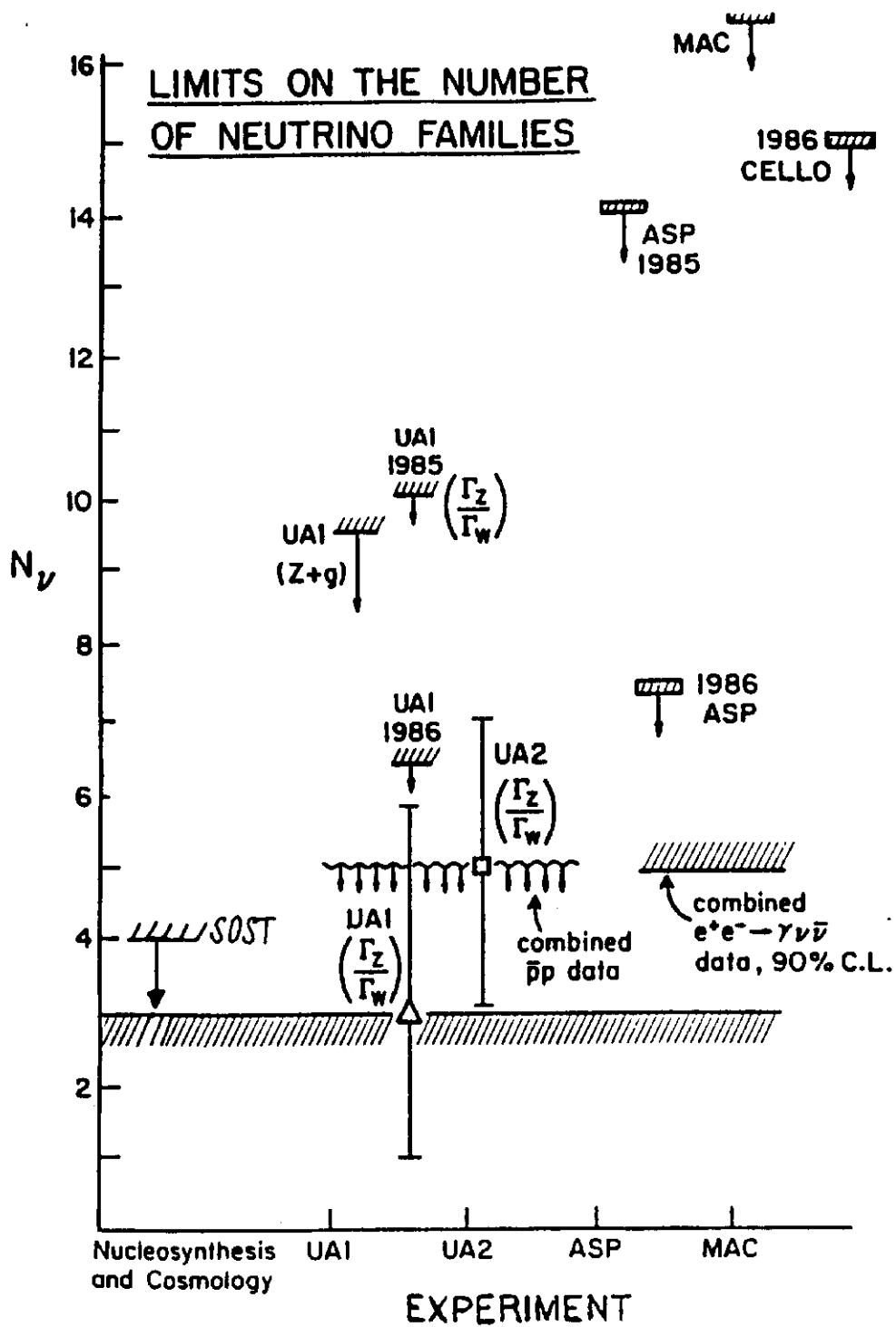
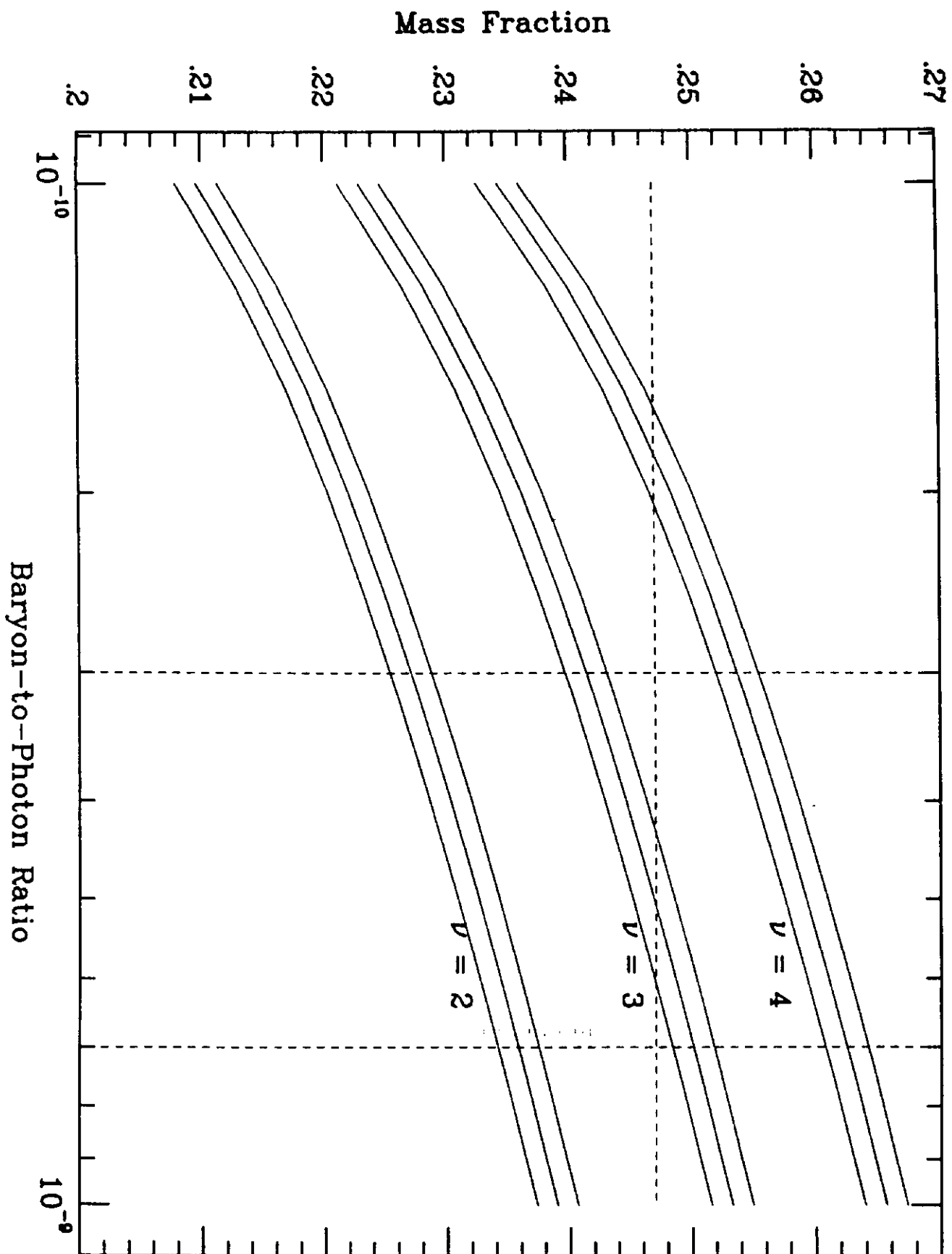FIGURE ⬇ Present limits to N_ν from cosmology, $\bar{p}p$ and e^+e^- experiments.

FIGURE 2